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Seabed-Structure Interactions in Coastal Sediments

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Abstract: Seabed-structure interactions are responsible for the burial of heavy objects, such as mines, pipelines, concrete breakwaters, platforms, and other objects on the seafloor. In low shear strength muds, these objects are known to bury at impact or to sink into the sediment if the buoyant weight of the object exceeds the bearing capacity of the seafloor. In higher energy sandy sediments, burial by scour and fill, momentary or cyclic wave-induced liquefaction, and seabed morphological changes (e.g., transverse bedform migration, changes in shore-rise and bar-berm conditions, sediment deposition) is common. Each of the possible burial processes will be discussed and an integrated, time-dependent object burial model will be proposed. Results from three recent burial experiments on cylindrically shaped objects will be used to demonstrate burial by biological processes, scour/fill and changes in near-shore beach and bar morphology, and subaqueous dune migration.

Introduction

Buried mine detection has been and is still one of the greatest threats facing Shallow Water Mine CounterMeasures (SWMCM) operations (Richardson and Tooma, 1993; Lott, 2000). The possible presence of buried mines can change MCM tactics from one of mine hunting to one of minesweeping or area avoidance. The ability to predict mine burial both for planning and during operations (strategic and tactical scenarios) is therefore of great importance to Naval forces. Processes known to contribute to mine burial include burial at impact usually in low strength muddy sediments; scour and fill; bedform migration or transverse bedform movement; bedform morphological alterations, such as changes to shorerise or bar-berm conditions; liquefaction or fluidization of the sediment; and biological processes that scour or alter seafloor roughness or sediment physical properties. U.S. Naval scientists have developed three burial prediction models that can be used for MCM tactical planning and for development of environmental support products: impact burial, sand ridge migration, and wave-induced scour. All of these models, first developed in the 1960s-1980s, are simplistic, empirically based, and static (i.e., no time dependence); do not account for all burial processes; treat burial as single rather than interacting processes; and, except for burial by impact, all mine burial models have limited experimental verification. Only the impact burial model has been subject to frequent improvements.

It is the purpose of this article to present the framework for a new, integrated, time-dependent, mine burial prediction model useful for both a) long-term burial prediction based on historical databases and fleet numerical meteorological and oceanography prediction models and b) real-time, in-stride mine burial prediction based on updates with environmental measurements made with systems organic to fleet assets. The results of three mine burial experiments using the newly

developed instrumented mine demonstrate burial by biological processes, scour/fill and changes in nearshore beach and bar morphology, and subaqueous dune migration.

An Integrated Mine Burial Model

NRL has developed the framework for a new mine burial model (Fig. 1), based on an extensive review of the mine/object burial literature (Lott, 2000), participation Mine Burial Specialist Team (NATO Subgroup 31; January 1995 – December 1998) meetings, and experiments in the North Sea (Anonymous, 1999). This model recognizes that mine or object burial is time dependent and that burial processes are not independent. Time dependent mine burial is predicted from numerical oceanographic models or in situ measurements of wave climate and tidal and storm-induced bottom currents; sediment physical properties and small-scale morphological features measured in situ or compiled in historical databases; and characteristics of the mine threat based on intelligence. The model provides both strategic and tactical mine burial prediction.

The impact burial model, first proposed by Arnone and Bowen (1980), is probably the most widely used and modified, physically sound, and extensively tested of the mine burial models. The model provides a time history of mine movement based on forces and torques on a cylindrical mine as it passes through air, water, and into the sediment. Burial occurs quickly in low-shear-strength, muddy sediments. Environmental inputs (gradients of sediment bulk density and shear strength) together with mine characteristics (D) are sufficient to accurately predict burial of cylindrical-shaped or tapered mines but impact burial of modern non-cylindrical mines may not be accurately predicted. Sediment shear strength and bulk density gradients are typically based on core samples, in situ penetrometers, or acoustic sediment classification systems.

Both near-field and far-field processes can further bury objects on the seafloor. Far-field morphological changes of the seafloor are unaffected by the presence of mines, and mine characteristics (D) are only considered as part of the geometric aspects of burial. A great variety of seabed features can be found in estuaries, beaches, and shallow coastal regions. Many of these features are in equilibrium with modern hydrodynamic conditions (e.g. not relict) and their size, location, and morphology over time can be predicted from measured or predicted oceanographic conditions (A & B) and seafloor properties (C). Several geometric models have been proposed to predict mine burial by migrating sand dunes. These models require information on dune dimensions and migration rates, which can either be measured directly or predicted using sediment transport models (see Soulsby, 1997). Changes in equilibrium beach profiles, especially the movement of offshore bars, can also be predicted from values of sediment properties and wave climate. Changes in these beach profiles are related to either seasonal changes in wave climates (Inman et al., 1993) or to the effects of major storms (Lee et al., 1998).

Near-field burial processes (scour and fill, liquefaction, and biological processes) are all affected by the presence of the mine. Scour, caused by turbulent flow around mines under the influence of oscillatory waves, currents, and tides, has been modeled by a variety of empirical and physics-based models. Many of these scour models are based the empirical formulations developed for bedload and suspended load sediment transport around cylinders and are based on the laboratory

flume studies of Carstens and Martins (1963). Other models simply add an enhancement factor to standard sediment transport models (bed shear stress required to initiate bedload and suspended load transport from tidal and wave-induced currents) to account for the added turbulence caused by the mine's presence (see Whitehouse, 1998). Inman and Jenkins (1996) developed a more sophisticated scour model to account for burial of mines by scour and changes in beach profiles. Turbulent flow around an arbitrary mine shape on the seafloor is modeled as horseshoe-shaped bound and trailing vortices initiating from the mine shape. The summed velocity field resulting from these vortices is used to calculate scour around the mine. The model accommodates a variety of mine shapes, provides time-stepped scour for varying flows, provides motion equations to allow prediction of mine movement during burial, and allows for seasonal changes in the beach profile. In general, scour and fill burial models require a time history of near bottom currents (based on tidal or wind-driven currents), surface gravity wave spectrum, sediment grain size and bulk density, seafloor morphology, and mine characteristics as model inputs. Liquefaction/fluidization of the seafloor can occur by momentary or cyclic liquefaction (Brandes, 1999). In either case when the build-up of excess pore pressure within the sediments exceeds the vertical stress of the sediments (which results from the self-weight of the grains), sediments lose their shear strength or bearing capacity and the mines sink based on their buoyancy in the liquefied sediment. Burial by liquefaction is controversial topic and numerous momentary and cyclic liquefaction models exist but none have been validated by adequate field experiments. Biological processes can physically both scour and infill around mines. Objects such as mines are known to attract a variety of larger benthic and pelagic animals by providing food and habitat. The activities of these animals can change seafloor physical properties as well as microtopographic roughness near a mine. Depending on the activities sediment transport can be either accelerated or retarded.

The Instrumented Mine

One of the major problems in the experimental validation of mine burial models is the difficulty of continuous measurement of the behavior of the mine. In past experiments, qualitative observations by divers were limited to 1-2 times a day and then only during good weather conditions. Burial is an episodic behavior often triggered by storms or strong tidal currents. Divers rarely observe either mine movements or the actual burial process but instead observe the end conditions. Laboratory experiments have difficulties related to scale, especially concerning sediment grain size, surface gravity wave height and period, bedform size, and mine shape, size and weight. The instrumented mine provides a tool for continuous monitoring of the movement of the mine (heading, pitch and roll) as well as the percentage of the surface area of the mine actually buried. The NRL design is based on an instrumented mine developed by Ingo Stender of Forschungsanstalt der Bundeswhr für Wasserschall- und Geophysik in Kiel, Germany. Heading ($\pm$ 1°) is measured with three solid-state compasses and roll and pitch ($\pm$ 3°) of the mine are measured with three-axis accelerometers. Burial is measured by three rings of paired optical sensors externally mounted at 15° intervals around the mine. Transmitting optical sensors are LED's and receiving sensors are phototransistors. The mine in Figure 2 is made of aluminum and is 1.5 m long and 0.47 m in diameter. The weight in air is 619 kg and in water is 357 kg but these weights are adjustable. During the experiments described below, measurements were made every

30 minutes and stored on an internal 1-Gbyte hard drive. Given the power requirements and battery capacity, measurements can be made every 30 minutes for 90 days.

Mine Burial Experiments

Panama City: A successful functional test of the instrumented mine was conducted on a sandy substrate off Panama City, Florida 10-25 June 1999. The mine was gently lowered to the sediment surface, a well sorted, fine sand (0.25 mm mean diameter) with 39% porosity and 2024 kg m^{-3} bulk density. Changes in depth of burial of the mine over the 15-day period were minimal. The line-of-sight between sets of optical sensors 11-14 was broken by the presence of sand during most of the deployment (Fig. 3). These 4 optical sensors transcribe an arc of 60° in contact with the sandy sediment, representing a 7% depth of burial. Changes in apparent burial from 10-22 June are probably a result of scour by fish and blue crabs (Fig. 4). This construction of scour pits is related to feeding or securing habitat or refuge from predation. The front (1) and middle (2) rings were subject to apparent burial (90° arc or 14% burial) 22-24 June. Divers observed small mounds of sediment piled up against the rings apparently created by crabs. The observed biogenic sediment movement and lack of change of heading, roll, or pitch of the mine suggest the movement of sand was unassociated with physical processes. The low sea states and weak bottom currents observed during the deployment period support this conclusion.

Scripps Pier: A second set of experiments was conducted off the Scripps Pier in 8-m water depth from 25 July to 19 September. Sediments were well-sorted fine sand (0.19 mm mean diameter). Initially there was some burial of the mine followed by scour around both the end ring (Ring 1) and the middle ring (Ring 2) between the 3rd and 6th days after deployment (Julian dates 211-214) (Fig. 6). Seven days into the deployment (Julian date 215) onshore-directed sand movement began and ring 1 and the middle of the mine were buried (up to sensors 9-20) by the 17th day (Julian date 225). This maximum burial included sensor pairs in an arc of 180°, equivalent to 50% burial. After the 35th day (Julian date 243) the mine began to uncover and did not approach 50% burial until the 53rd day (Julian date 261), near the time of recovery. The end of the mine with the simple flat end (Ring 3) did not bury much (up to sensor pairs 13-17, or 10% burial) and was the site of bed armoring resulting from winnowing of sand and scavenging of cobble-sized gravel (Fig. 5). The orientation of the mine changed slightly, first in response to local topography, and then on the 23rd day in response to a shift in shoaling wave direction. The waves changed to a slightly more southerly direction resulting in only a 1° counter clock wise (CCW) shift in the mine's orientation. Changes in roll and pitch due to changes in wave direction were minimal (2-3°). The rate of burial of the NRL mine will be compared to predictions by Scott Jenkins and Doug Inman (Scripps Institution of Oceanography) of a) near-field burial by sediment transport by vortices shed from the mine shape (vortex lattice method) and b) far-field burial and exposure by changes in beach profiles due to accretion and erosion. Wave energy, period, and direction were measured both at the end of the Scripps pier and by a directional wave rider buoy west of the pier in 180 m water depth.

East Pass (Destin Florida): A mine burial experiment was conducted in East Pass, Destin Florida during October 1999. The tidal pass is the only direct entrance between the Gulf of Mexico and Choctawhatchee Bay and the seafloor is characterized by migrating sand dunes

(Wright et al., 1972; Morang, 1992). A series of active dunes were located west of the navigation channel and south of the Destin Bridge using echo sounding. Divers, with the aid of lift bags, placed the mine 1 meter in the path of a migrating dune, in 4 meters water depth (Fig. 8). In response to the alternating tidal flow, the mine almost immediately (within 8 hours after deployment) rotated into the current (heading changed from 175° to 160°), rolled clockwise 4°, and pitched down 4.5°. After 4-5 days the migrating face of the dune had reached the first ring and the mine was completely covered after 11 days (Fig. 8). The mine remained covered for the duration of the experiment (18 more days).

Sediments in East Pass were medium, well-sorted sands (0.49 mm mean grain size) with 37% porosity and 2060 kg m^{-3} bulk density. Tidal currents during the experiments were typical of East Pass (Morang, 1992) with stronger ebb than flood tides (Fig. 9). Morang (1992) attributes the comparatively long duration and high velocity flood tide to hydraulic amplification from freshwater inputs into Choctawhatchee Bay from rain and river runoff. The threshold of sediment motion (calculated from the water depth and sediment type) is exceeded on both ebb and flood (Fig. 10) suggesting alternating seaward and bay-ward movement of the dune face, with the seaward migration dominant as a result of the longer duration and higher velocity of the ebb tide. This alternating seaward and bay-ward dune migration is evident on all three rings of the mine (Fig. 9).

The threshold of sediment motion for sand with a mean grain size of 0.49 mm at 4-m water depth is approximately 0.4 m s^{-1}, which was exceeded during virtually every tidal ebb and flow (Fig. 10). The average time for initial burial of a mine or the steady-state percentage burial of mines in this portion of East Pass can be calculated from the migration rate and shape of the dunes and the dimensions of the mines. Sand dune length and height were 30 m and 0.6 to 0.8 m, respectively, with a migration speed of 0.3 m d^{-1}. The average time for initial burial of mines randomly placed in East Pass is therefore 50 days and the percentage of fully buried mines after 100 days ranges between 30-70% depending on the value of the dune height. The dune dimensions (height and length) can also be estimated from water depths and bed shear stress (based on sediment mean grain size, water depth, and current speeds) and the migration rate of the dunes can be estimated from the dune shape and rates of bedload transport. Rates of bedload transport vary by as much as a factor of 4, depending which transport formula is used (Soulsby, 1997).

Conclusions and Planned Experiments

The experiments conducted to date provide a test of some of the measurement systems to be used for experiments planned for FY00-02 and were not designed as test of specific mine burial models. The results presented here should be considered both preliminary and serendipitous to the ultimate objectives of the "Mine Burial Process" program being conducted at the Naval Research Laboratory, Stennis Space Center.

Mine burial experiments are planned for the high-energy nearshore environments of Duck, NC. In these experiments we will attempt to quantify the relative importance and interactions of scour, liquefaction, and bedform alteration. The conditions under which momentary or cyclic liquefaction is a significant contributor to mine burial will be quantified and the relative

importance of liquefaction as a precursor to scour will be determined. Future experiments will determine the bed stress conditions necessary to initiate sand motion in the presence of a mine and compare rates of scour based on empirical bedload stress and transport, and finite element turbulent flow predictions. Experiments in tidally dominated environments will be used to quantify the interaction of bedform (subaqueous dunes) migration and scour and to quantify the environmental forcing functions leading to sediment transport, bedform migration and scour. The overall objectives are to determine the conditions where various mine burial processes dominate; provide rigorous tests of proposed mine burial models; and ultimately develop and validate an integrated mine burial prediction model such as proposed in Figure 1.

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The instrumented mine was designed by David Young and Jason Mimms (both of NRL) and built by OMNI Technologies. We especially thank Sean Griffin, John Bradley (OMNI) for their expertise and participation in the experiments. Ricky Ray and Dan Lott (NRL divers) assisted with deployment and recovery of the mine in the East Pass and Panama City experiments. Scott Jenkins organized and provided logistical support for the experiments off the Scripps Pier. Conrad Kennedy and Rick Mang provided logistical support for the East Pass experiments. We also thank LTJG Mike DeHoyos and Chief Craig Smith, and the students and instructors of Naval School, Explosive Ordnance Disposal (NAVSCOLEOD) Detachment at Eglin AFB for recovering the completely buried instrumented mine at the conclusion of the experiments in East Pass, Destin, Florida. Phil Valent (NRL) provided valuable review comments.

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Figure 1. Flowchart for an integrated mine burial model

Figure 2. The NRL instrumented mine being deployed in the East Pass of the Destin Inlet, northeastern Gulf of Mexico (Photograph by Ricky Ray).

Figure 3. Mine burial measured at a shallow water (8 m) site 150 m off the beach at Panama City, Florida. The shaded areas represent a blocked passage of light between pairs of optical sensors that are located every 15° on three rings around the instrumented mine (see Figure 2).

Figure 4. A Blue Crab is protecting its territory from scuba divers. The crab and fish scour the seafloor and create mounds around the instrumented mine at the Panama City site giving the appearance of burial and unburial on the optical sensors (Photograph by Ricky Ray).

Figure 5. Scour and fill (left) and bed armoring (right near Ring 3) around the instrumented mine during deployment off the Scripps Pier (Photographs by Scott Jenkins)

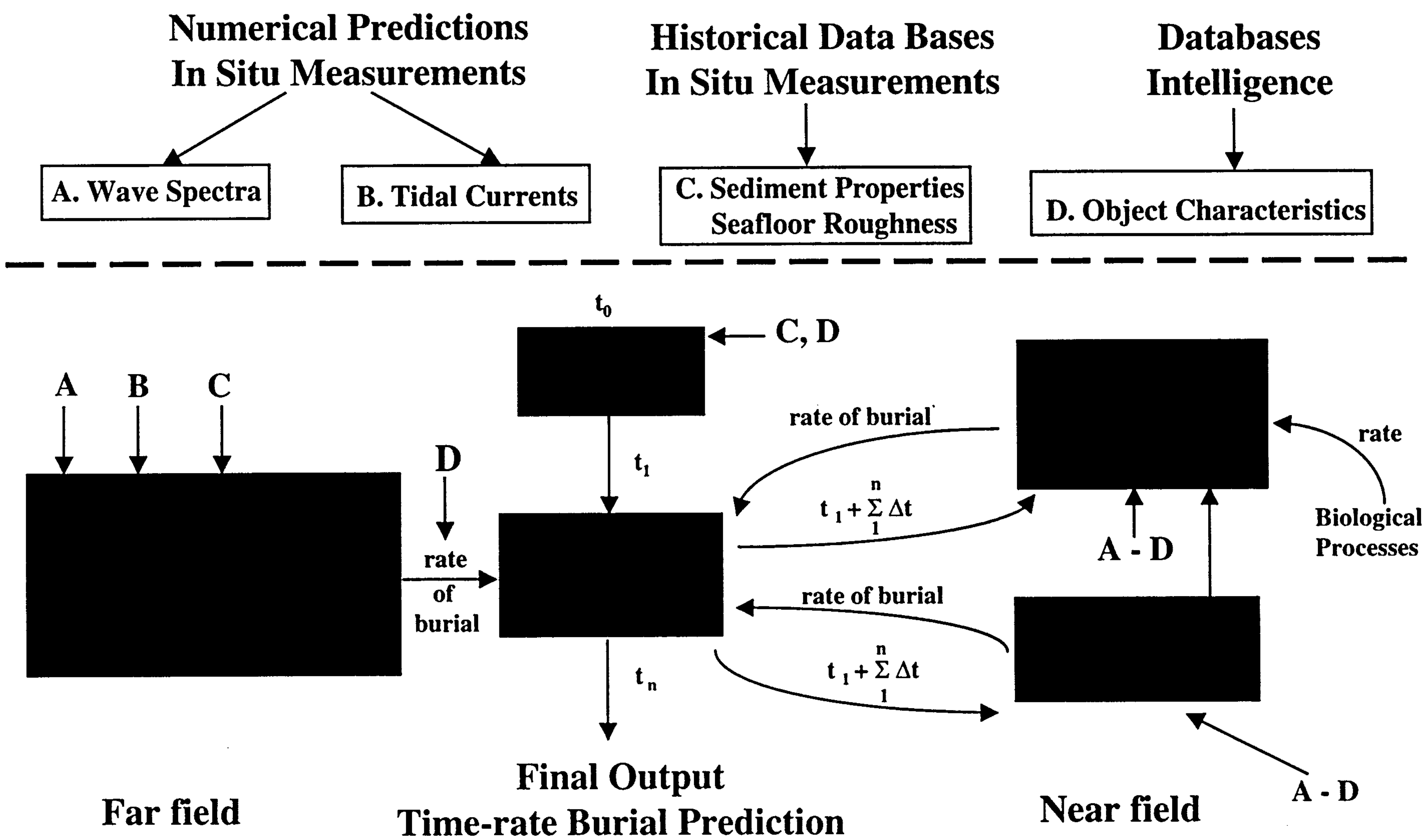
Figure 6. Mine burial measured at a shallow water (8 m) site 5m off the Scripps Pier, San Diego California. The shaded areas represent a blocked passage of light between pairs of optical sensors that are located every 15° on three rings around the instrumented mine (see Figure 2).

Figure 7. Instrumented mine at the beginning of experiments at East Pass, Destin Inlet, northeastern Gulf of Mexico. The face of a migrating subaqueous dune is evident in the background. The dune face is 0.60 to 0.80 m in height and is migrating towards the mine.

Figure 8. Mine burial measured at shallow water (4 m) site within East Pass, Florida. The shaded areas represent a blocked passage of light between pairs of optical sensors that are located every 15° on three rings around the instrumented mine (see Figure 2). Note the order of burial of the three rings of optical sensors. Ring 1 was closest to the face of migrating dune.

Figure 9. Speed and direction of tidal currents in East Pass, Florida measured 18 m south of the instrument mine using an RDI Acoustic Doppler Current Meter (ADCP). Current direction was predominately 330° during flood and 150° during ebb flow.

Figure 10. The speed of tidal currents in East Pass Inlet, Florida (see Figure 10). The threshold of sediment motion is exceeded during both ebb and flood tides.



Numerical Predictions
In Situ Measurements
A. Wave Spectra
B. Tidal Currents
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C. Sediment Properties
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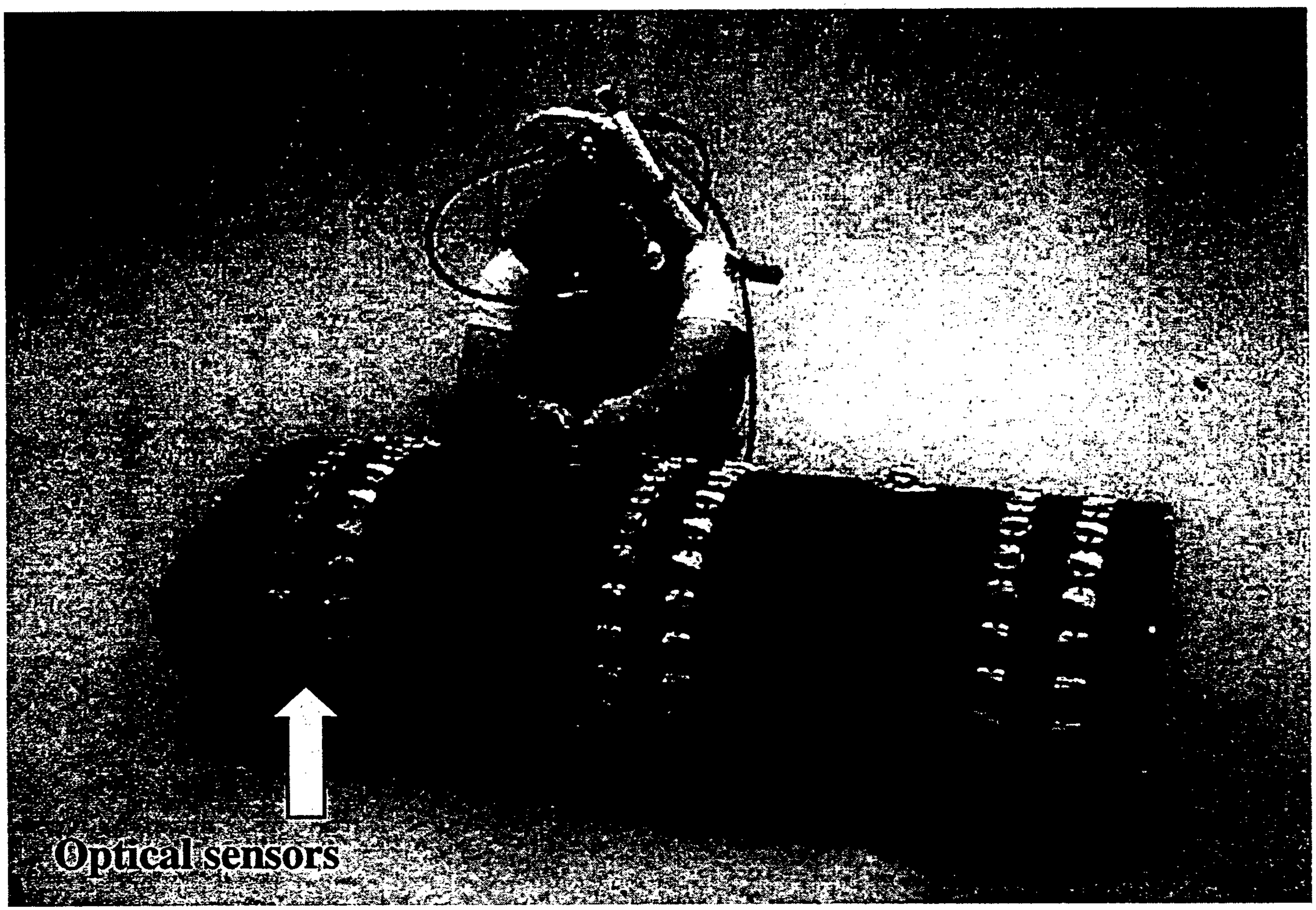
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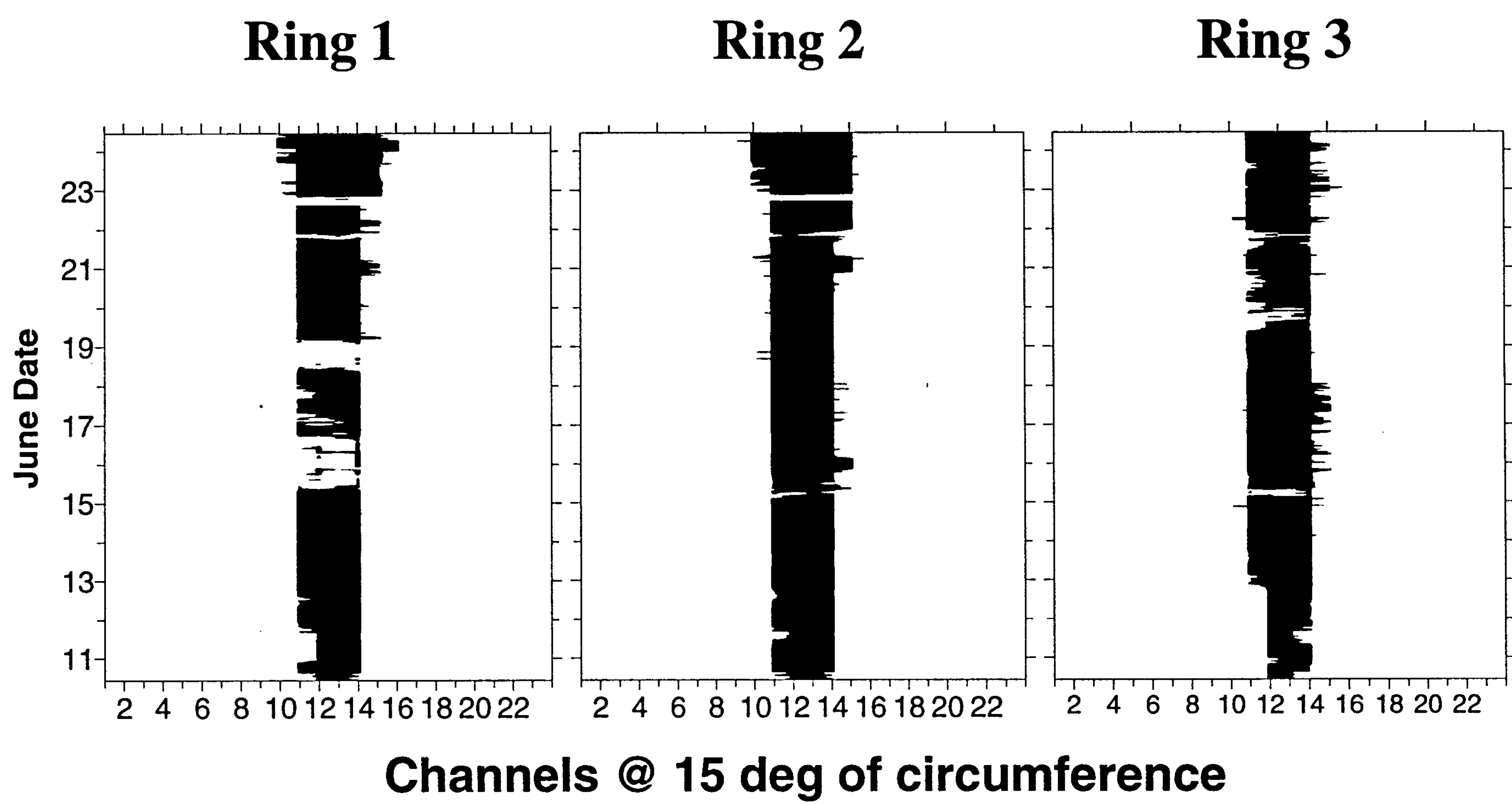
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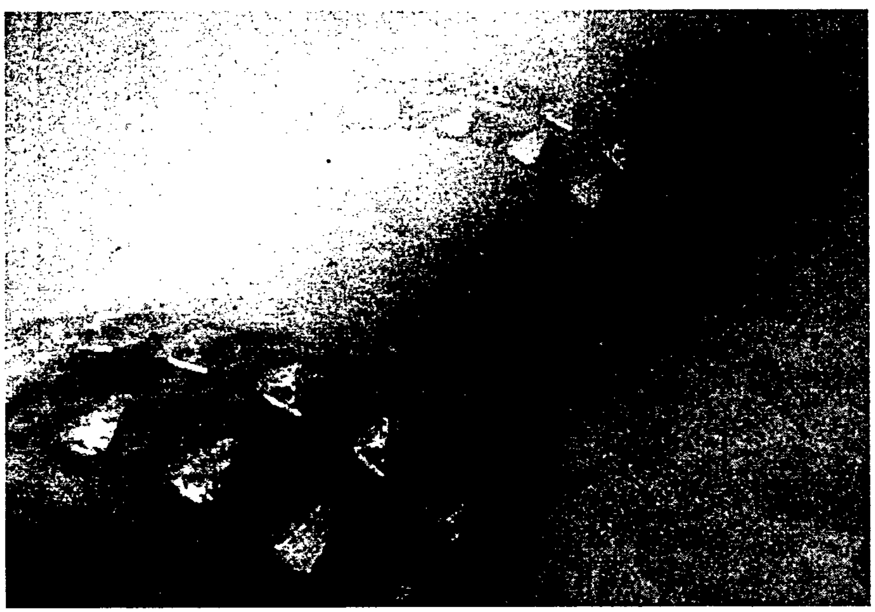
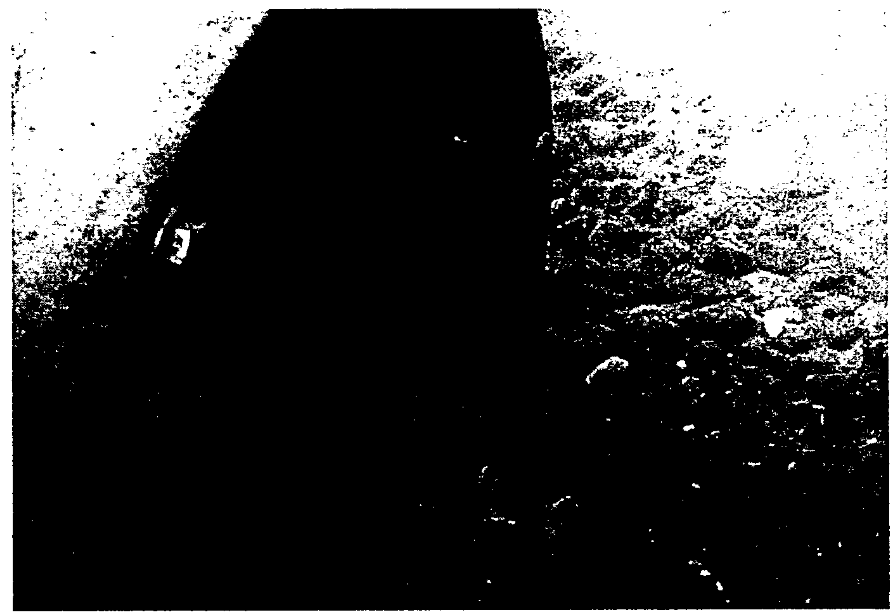
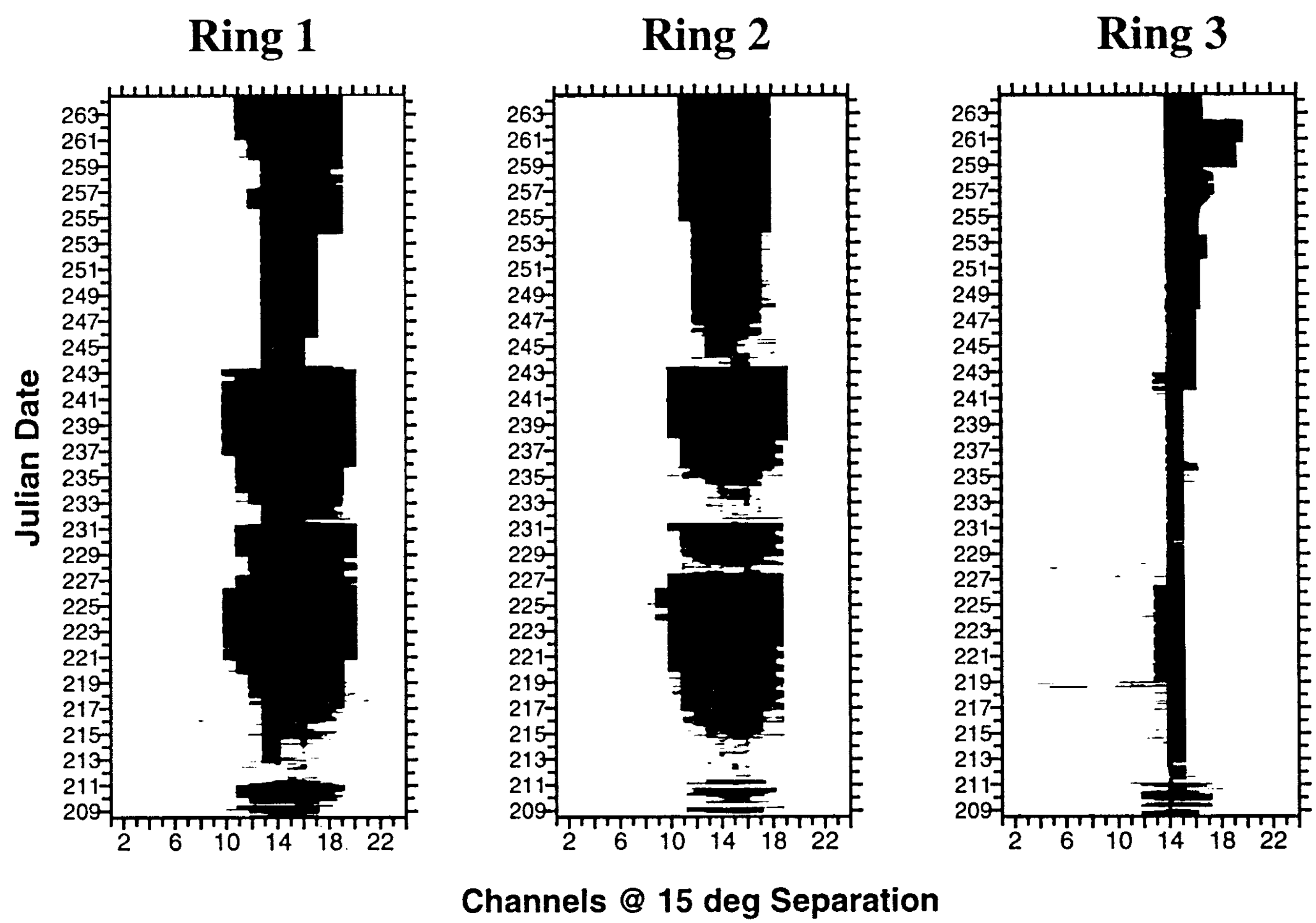
Scour, infilling and reorientation to currents



Scour resulting in bed armoring at end of mine

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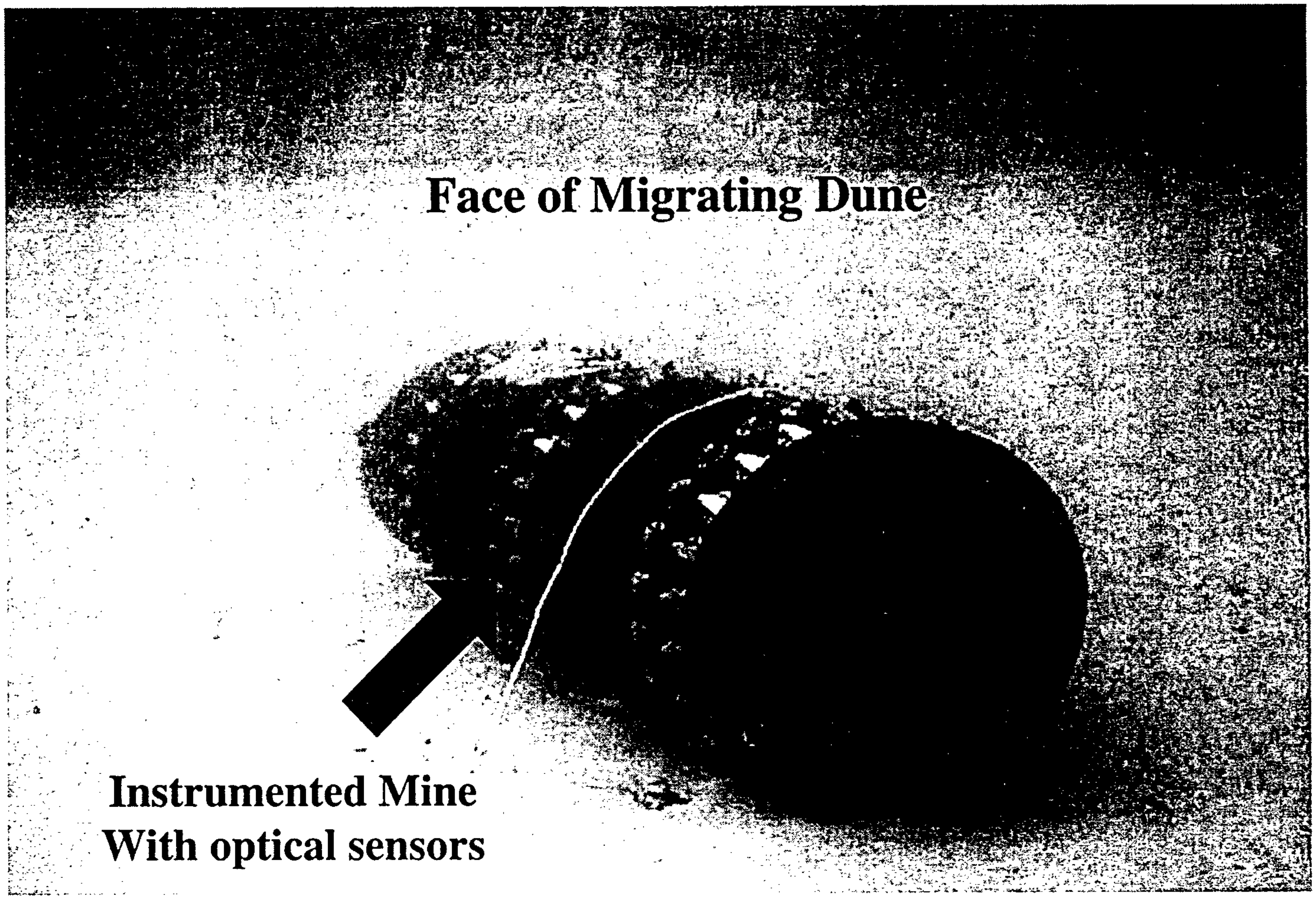
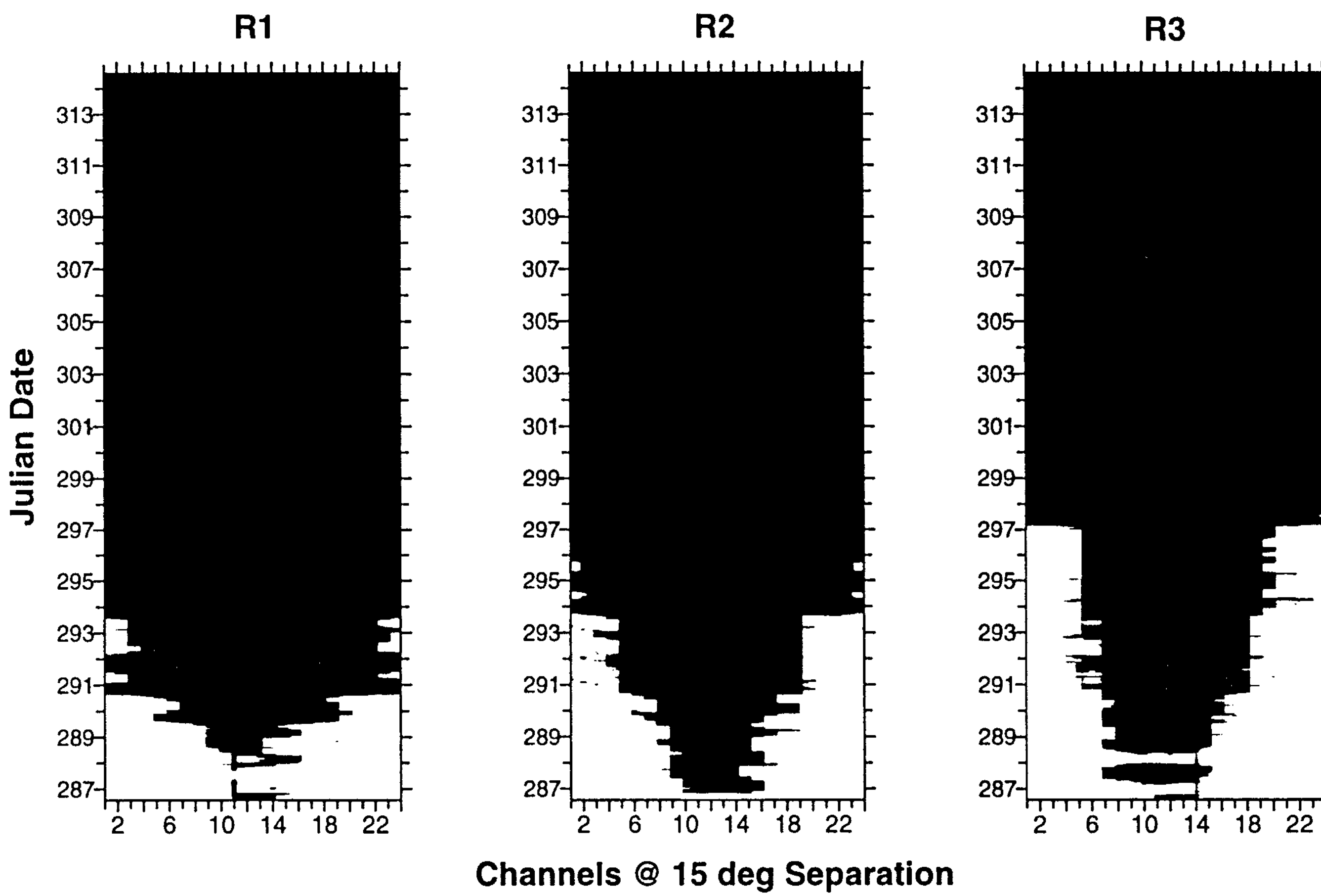

Face of Migrating Dune
Instrumented Mine
With optical sensors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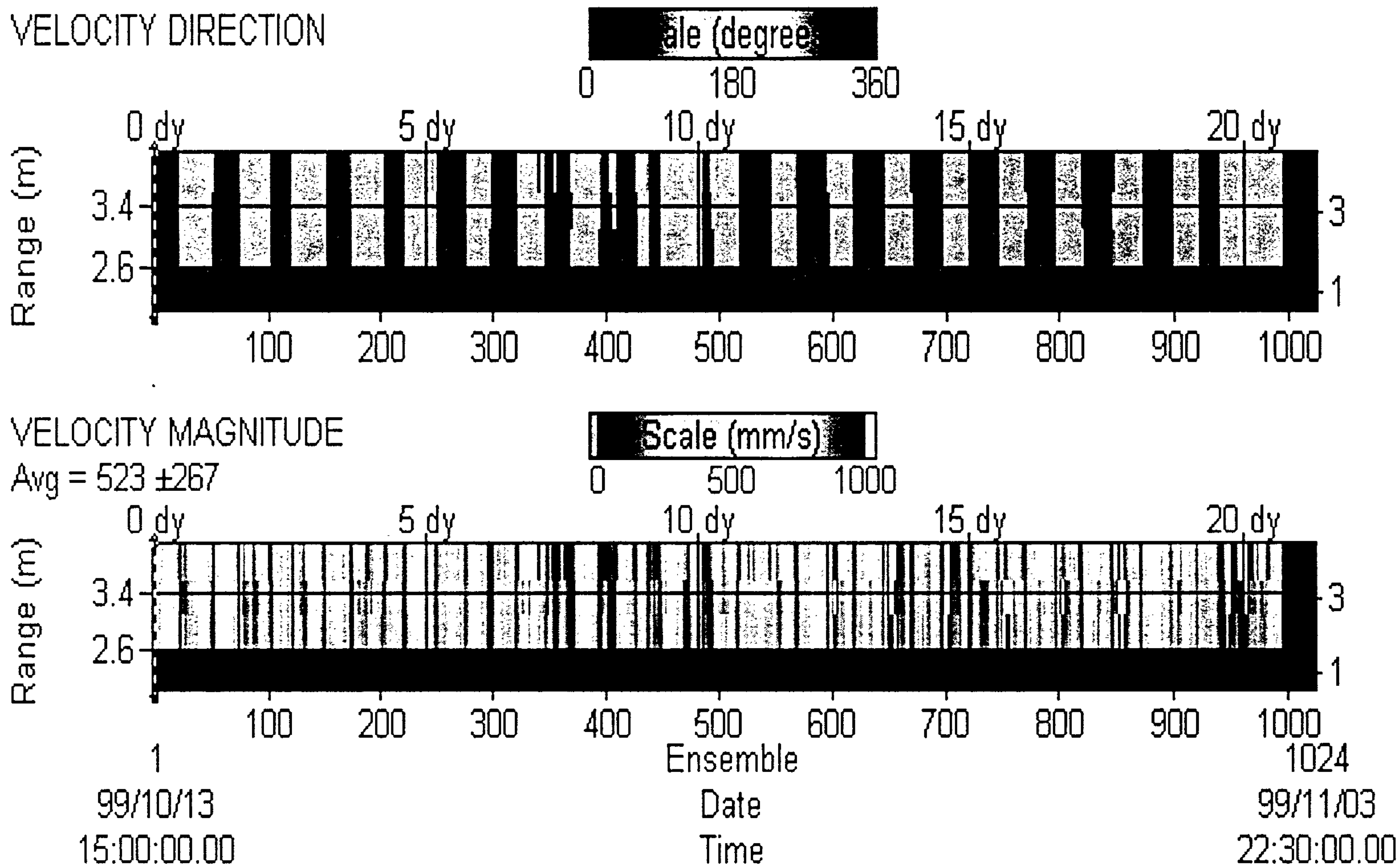

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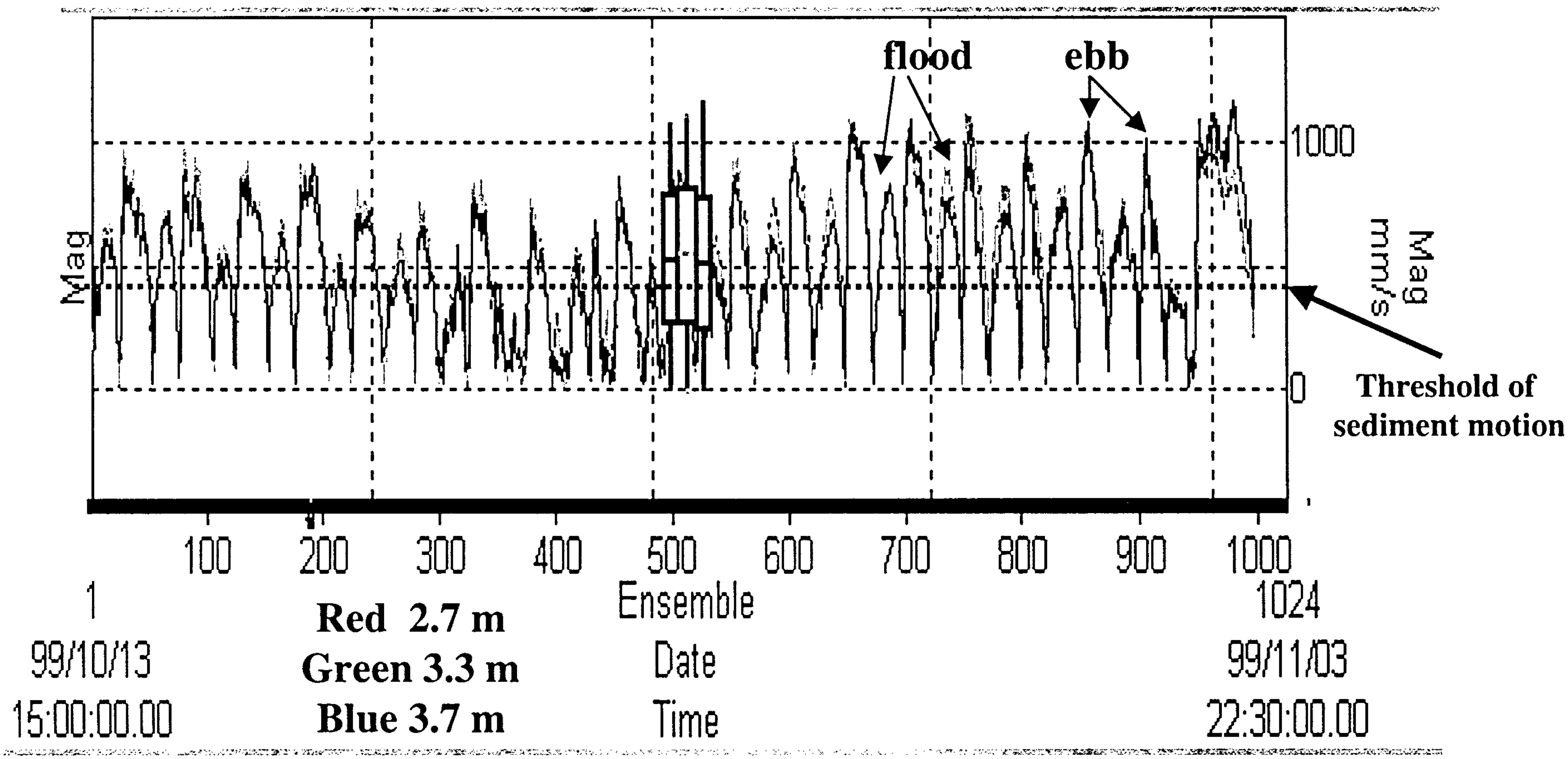
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